

DISTRIBUTED PHASED ARRAY ARCHITECTURE STUDY

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The hardware tolerances needed to successfully operate distributed phased array antennas in a space environment are not clearly defined at this time. Variations in amplifiers and phase shifters can cause degraded antenna performance, depending also on the environmental conditions and antenna array architecture.

The implementation of distributed phased array hardware has been studied with the aid of the DISTAR computer program as a simulation tool. The principal task of this simulation is to provide guidance in hardware selection. Both hard and soft failures of the amplifiers in the T/R modules are modeled. Hard failures are catastrophic - no power is transmitted to the antenna elements. Non-catastrophic or soft failures are modeled as a modified Gaussian distribution. The resulting amplitude characteristics then determine the array excitation coefficients. The phase characteristics take on a uniform distribution.

Pattern characteristics such as antenna gain, half-power beamwidth, mainbeam phase errors, sidelobe levels, and beam pointing errors have been studied as functions of amplifier and phase shifter variations. General specifications for amplifier and phase shifter tolerances in various architecture configurations for C-band and S-band have been determined.

NASA Colleague: G. Dickey Arndt EE3 X2128

INTRODUCTION

The distributed architecture concept in phased array antennas incorporates transmit/receive (T/R) modules at or near the elemental radiators of the array. The most important components of the T/R modules are the high power amplifier (HPA) and the low noise amplifier (LNA). Major advantages of this approach include system reliability, improved system noise figure, mechanical deformation and motion compensation, and achievement of high total radiated power with solid state devices.

The most generic distributed array has an amplifier (or T/R module) at each radiating element. Due to limitations of cost or practicality, the array architecture may require reduction, so that one module may drive several elemental radiators. An important problem is to optimize antenna performance subject to the constraint of architecture reduction. Further constraints include the use of real rather than ideal electrical components, which are subject to both random and systematic errors.

To address this problem, a computer program named DISTAR has been created by PSL (Physical Sciences

Laboratory, New Mexico) and developed by NASA/JSC. The program inputs antenna array characteristics along with type and extent of amplifier performance failure and outputs the normalized antenna gain pattern in graphical and/or tabular form. Both hard and soft failures of the amplifiers in the T/R modules are modeled. Hard failures are catastrophic - no power is transmitted to the antenna elements. Soft failures are random perturbations of amplitude and phase from the ideal specifications.

The paper gives a brief description of the program DISTAR, followed by an analysis of the method used to construct the pattern. The final section discusses an application of the program to determine specifications for hardware tolerances for three distributed arrays, one at C-band and two at S-band.

PROGRAM DESCRIPTION

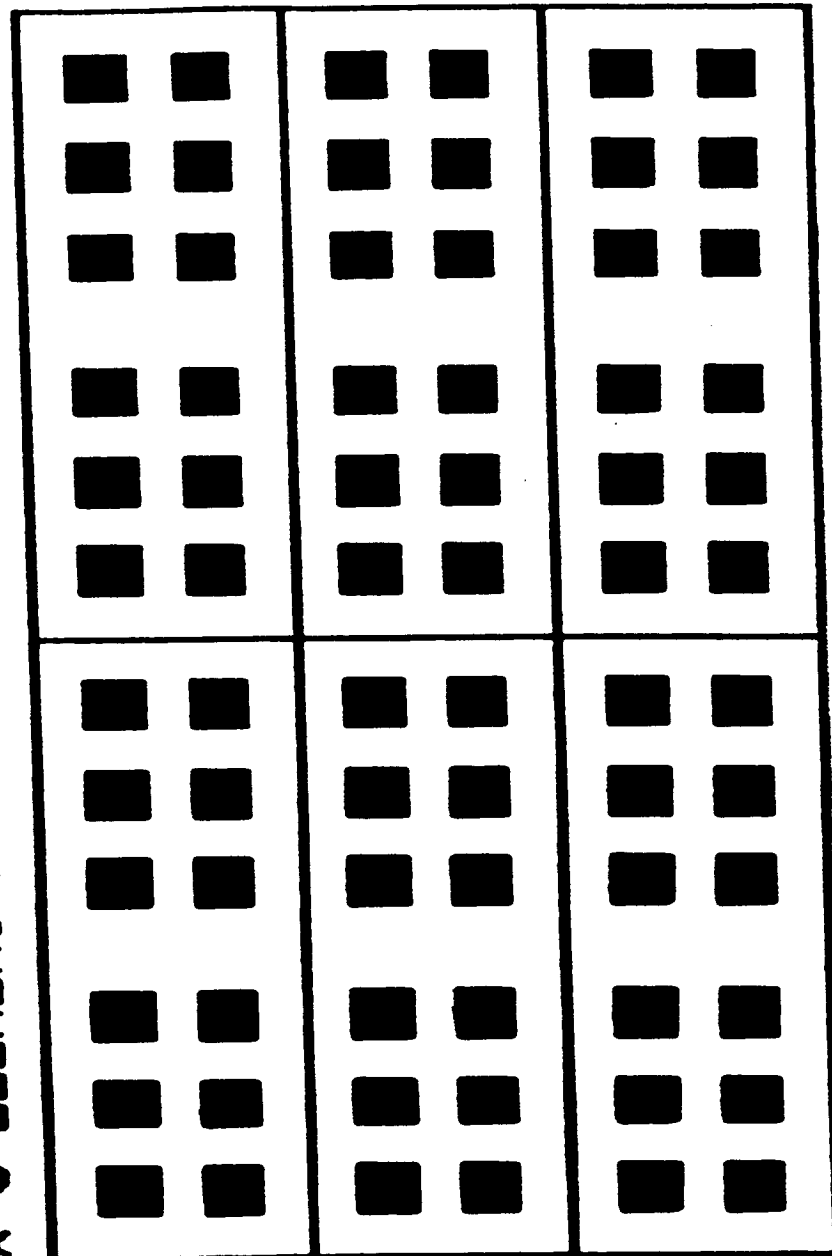
This section briefly describes the capability of the program DISTAR in terms of input and output. The array is rectangular. It may be divided, both physically and electronically, into various subarrays: panels, subgroups, co-phased elements, and co-amplified elements. The dimensions of these subarrays are all determined by the user. It may be useful to refer to Figure 1, which sketches a 12 x 6 element array with 6 panels and 3 x 2 element subgroups. The co-amplified groups are the panel rows.

Each panel is excited in amplitude and phase by user-specified amounts. A panel must contain an integral number of subgroups and co-phased groups. Each subgroup is physically separated from its neighbors by a uniform amount in x and y. Each element in a co-phased group is given an identical phase shift. Co-amplified elements are all driven by the same T/R module. The user specifies the spacing in x and y between elements and between subgroups, the frequency of the antenna, the element taper, the element pattern, the steering angle, and display mode(s) (2D graphs, 3D graphs, table).

Information about type and degree of hardware failure is input via program flags. If the user requests soft failures of the T/R modules, the program prompts for mean power, standard deviation in power, and range of phase distribution. (See next section for more detail.) If the user requests hard failures, the program prompts for whether the modules should be turned off randomly or systematically. If systematically, the user supplies the number turned off. If randomly, the user chooses whether to supply the number or have it also selected randomly.

GEOMETRY

12 X 8 ELEMENT ARRAY 3 X 2 ELEMENT SUBGROUPS



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FIGURE 1

THEORY

In this section, the equations used by the program to calculate the GAIN matrix are detailed. A brute-force method is used to sum the contributions of all the antenna elements to the field in a given direction. The GAIN matrix is calculated exactly once in the program and is subsequently used to display the information in the various forms requested by the user. For the convenience of the interested reader, the notation used in this section is identical to that used in the program.

For a given THETA and PHI, the linear complex array directivity AF2 is calculated in subroutine ARRAY as a sum over the contributions from the panels (see Section 1)

$$AF2 = \sum_{\text{panels}} A1 * SUBEF * EXP(iA2) ,$$

where

A1 = panel amplitude excitation coefficient

A2 = panel phase excitation coefficient

SUBEF = panel complex electric field

The array factor is given by

$$AF = |AF2|^2 * F / (MEL * NEL * POUT * XNORM) ,$$

where

MEL = the number of elements per panel in the
x-direction

NEL = the number of elements per panel in the
y-direction

$$POUT = \sum_{\text{panels}} (A1)^2$$

$$XNORM = \sum_{\text{all elts}} (ELWT)^2 / \#elts$$

ELWT = matrix containing the weights from the
element taper

$$F = \begin{cases} (1/16)[1 - \cos(\text{PI} - \text{THETA})]^4 & \text{if IELP} = 1 \\ 1 & \text{if IELP} = 0 \end{cases}$$

IELP = the element pattern flag

Then,

PHAS(THETA,PHI) = the complex argument in degrees
of AF2

and

GAIN(THETA,PHI) = $10 \log_{10} (AF)$ = AF expressed in
decibals.

The panel electric field SUBEF is calculated in subroutine SUBARY as follows:

$$\text{SUBEF} = \sum_{\substack{\text{elts in} \\ \text{panel}}} z w x P A ,$$

where

$$z = \text{ELZAP} = \begin{cases} 0 & \text{if element is zapped} \\ & \text{(catastrophic failure)} \\ 1 & \text{if element is not zapped} \end{cases}$$

w = ELWT = weight from the element taper

x = EXPHAS = relative phase shift of excitation to steer the beam to THETA0,PHI0.

x is a complex number of modulus one.

THETA0,PHI0 is the pointing angle.

P = PHASE = phase at current look angle. P is a complex number of modulus one

A = AMPWT = amplitude weight which models soft failures, as described below.

The amplitude weight A = AMPWT is calculated in subroutine AMPLWT as follows:

$$A = (a/u)^{1/2} \text{EXP(PHS)} ,$$

where

$$a = u + (-2*VAR*\ln X1)^{1/2} \cos(2*PI*X2)$$

$PHS = -j*DELTA*(1-2*X3)$ = uniform distribution
between $-DELTA$ and $DELTA$

u = mean of the distribution
(user-supplied = $AMEAN$)

VAR = variance = $SG*SG$ = square of standard
deviation SG
(SG is user-supplied)

$DELTA$ = range of phase distribution (user-supplied)

$X1, X2, X3$ are randomly generated real numbers
between 0 and 1.

ANTENNA TESTS

The program DISTAR described above was used to test three antennas for NASA, two at S-Band and one at C-Band. The problem was to determine the hardware tolerances necessary to operate these antennas in a space environment. With this model, this means to determine to what degree the amplifiers in the T/R modules can fail and still maintain an adequate antenna performance.

Two straightforward criteria were established to determine the hardware tolerances. First and foremost, the power at the maximum of the degraded beam should be within three decibals of the power of the maximum of the ideal beam. In other words, a falloff in power of more than fifty percent is not tolerated. Second, sidelobes of the degraded beam should not rise to within ten decibals of the mainlobe in the degraded beam.

Both hard and soft failures of the T/R modules were tested. Soft failures included both amplitude and phase errors. Different steering angles were employed. Warping of the panels was not included in the study. Principal plane cuts were obtained for all tests.

18 x 12 element C-Band

The frequency of this microstrip panel was 5.3 GHz. The spacing of the elements was 4.0 centimeters in the x-direction and 3.5 centimeters in the y-direction. Twelve T/R modules were employed, each controlling the eighteen elements in a row of the array. For the random fluctuations, the mean power was 10 decibals, with standard deviation 1 decibal and phase range distribution 10 degrees. The tests were run for two steering angles, i.e., broadside and $\Theta = 20^\circ$, $\Phi = 90^\circ$. Θ is the polar angle from the z-axis, and Φ is the azimuthal angle measured counterclockwise in the plane of the antenna from the x-axis. The conclusions for hardware tolerances were nearly identical for the two steering angles.

The conclusions are as follows:

- 1) Soft failures (random fluctuations in both amplitude and phase) have virtually no effect on the radiation pattern. One reason for this is that the fluctuations were small, the standard deviation of the amplitude variation being 10 percent of the mean, and the phase discrepancies being within 10 degrees.

2) The maximum acceptable level of hard failures is two. Beyond that, there is a high degree of probability that one or both of the above criteria will not be met. The degradation of the pattern is greatest when the failures are concentrated at the center of the antenna. With two hard failures, there is a very small probability that the sidelobes in the elevation plane will rise to within 10 decibals of the mainlobe.

2 x 4 element S-Band

Microstrip panels at two different frequencies were tested at S-Band. The frequencies were 2.1064 GHz and 2.2875 GHz. Since the results for the two frequencies are almost identical, only those of the former antenna will be reported here.

The spacing of the elements was 0.47λ in the x-direction and 0.56λ in the y-direction, where the wavelength λ equals 14.242 centimeters. Each array element was controlled by an independent T/R module. For the random fluctuations, the mean power was 7 watts, with standard deviation 0.5 watts and phase range

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distribution 25 degrees. Degraded patterns were desired for three different steerings: 1) broadside; 2) $\Theta = 90$ degrees, $\phi = 0$ degrees; 3) $\Theta = 45$ degrees, $\phi = 90$ degrees.

It was discovered that the antenna could not be steered to the directions 2) and 3) above. The maximum angle in Θ to which the beam can be steered is about 10 degrees. The probable cause for this phenomenon is a combination of two factors:

- a) the small number of elements;
- b) the element pattern $F = \{ (1/2)[1 - \cos(\pi - \Theta)] \}^{1/4}$.

The array factor produced by a) is not strong enough offset the contribution of b) at small values of Θ . The ratio of the element pattern for $\Theta = 0$ degrees to that for $\Theta = 90$ degrees is 16.

The conclusions for the broadside tests are as follows:

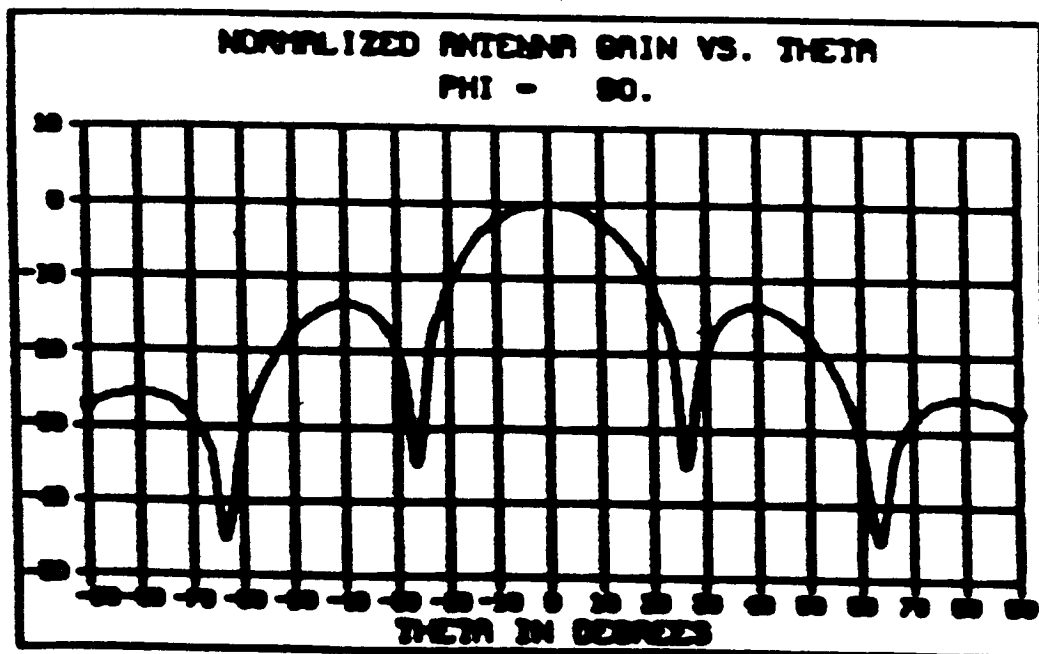
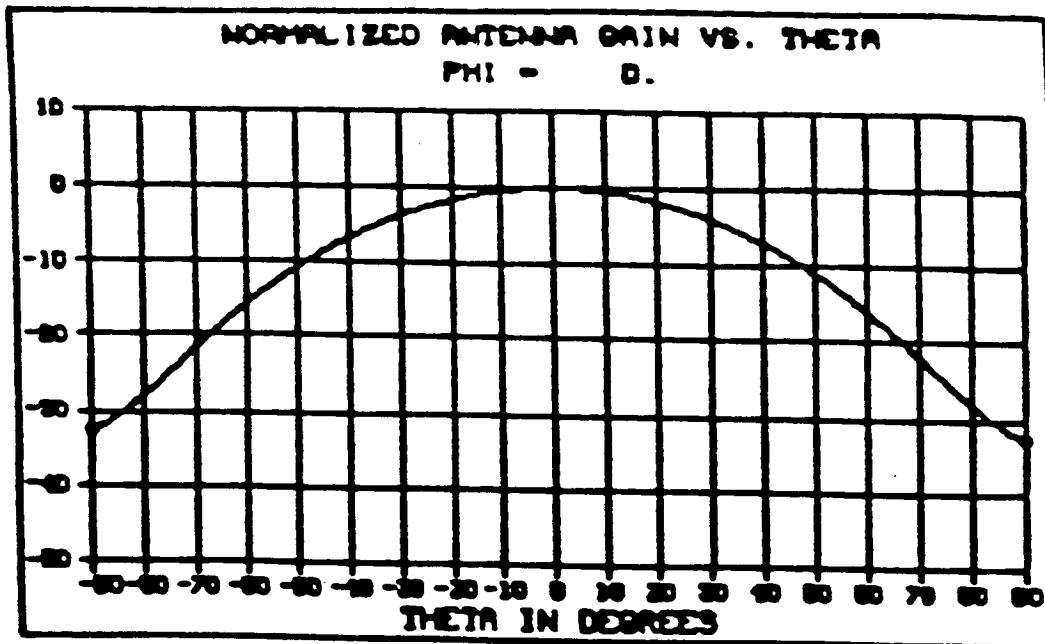
- 1) Soft failures have a negligible effect (less than 1 percent) on the maximum power levels due to the small standard deviation of 0.5 watts compared to the mean of

7 watts. However, they appear in some tests to contribute to a small (less than 1 degree) drift of the mainlobe and, when combined with hard failures, to undesirably high sidelobe levels.

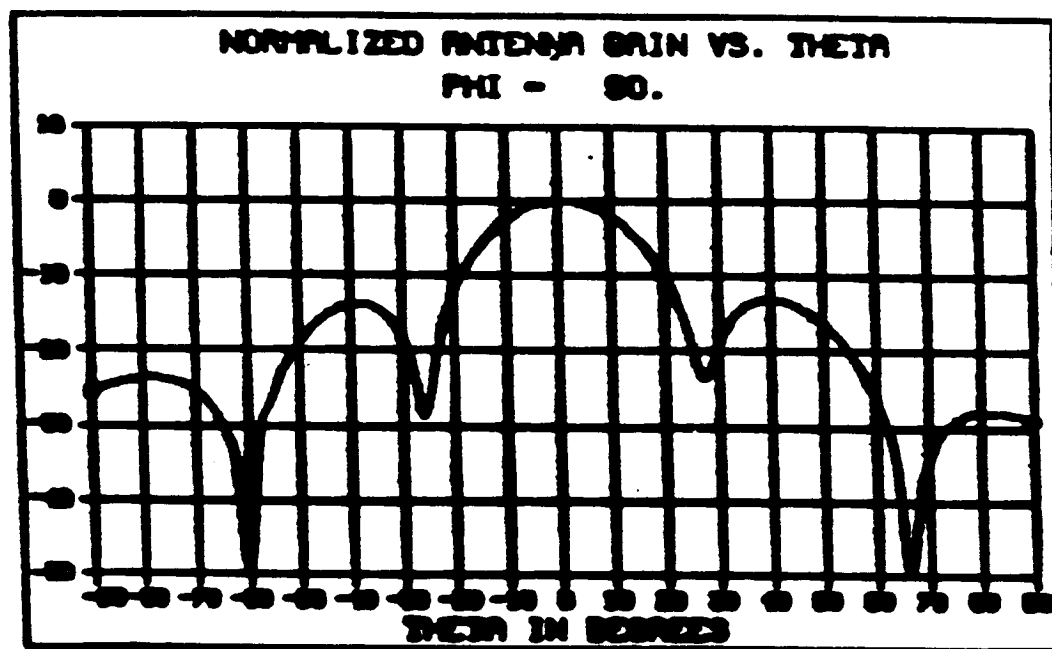
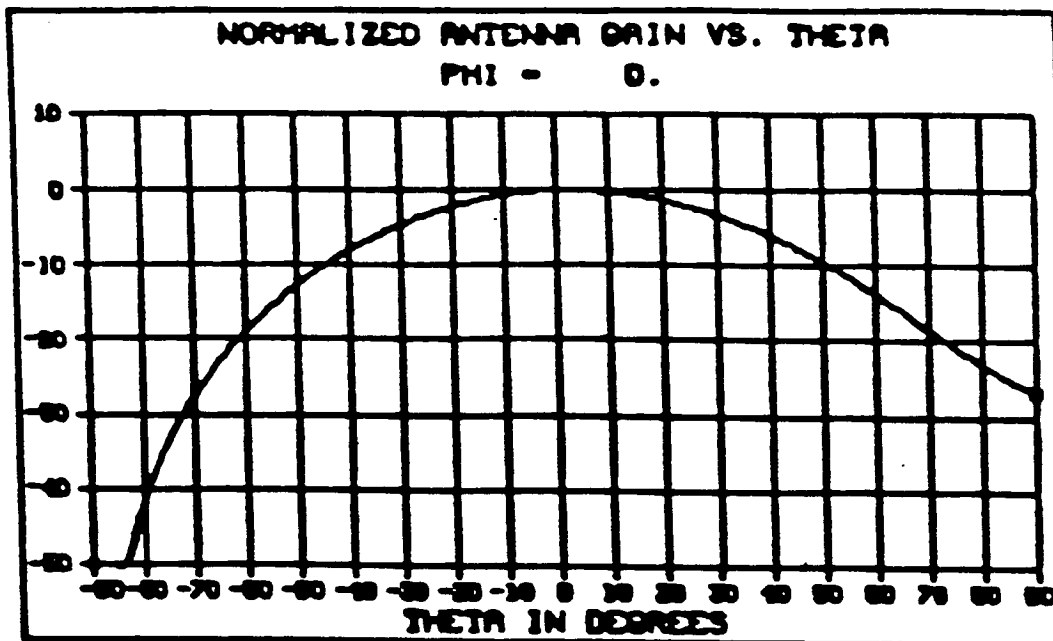
2) The maximum acceptable level of hard failures is two. With three hard failures, the average loss in decibals at the maximum is greater than 4. With two hard failures, the average loss in decibals is between 2.5 and 2.6 , with one pattern measured at 2.96 . With soft failures, there is about a 20 percent chance that a sidelobe could rise to within 10 decibals, even within 6 decibals.

Graphical displays of the results are given in Figures 2-6. Since the gain shown is normalized, however, one must examine tabular output to determine absolute power levels.

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IDEAL
2 X 4 ELEMENT 8-BAND
FIGURE 2



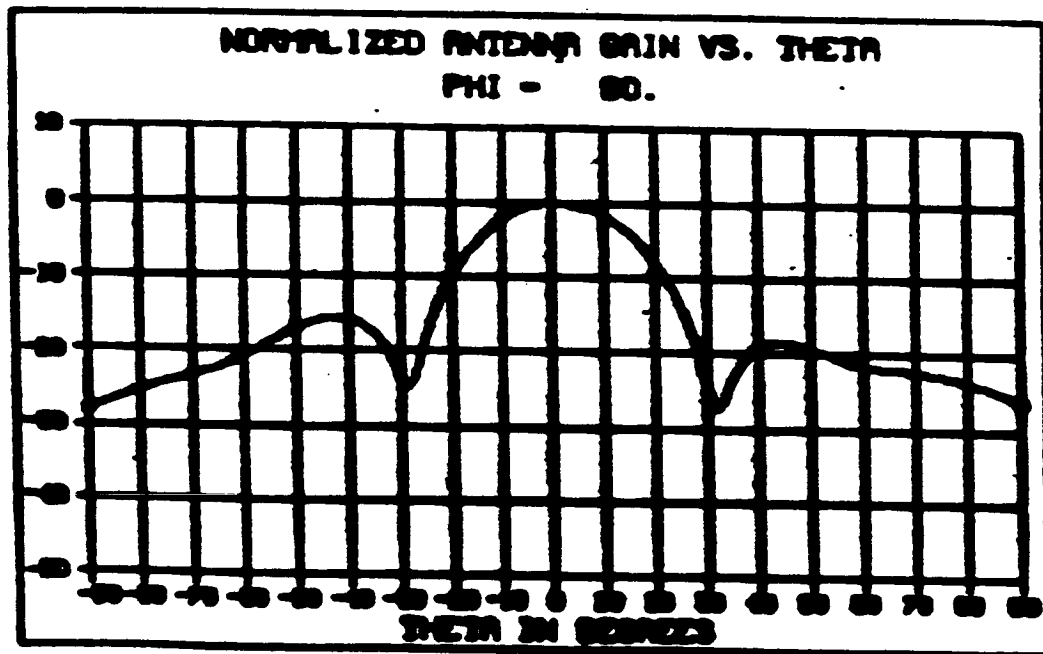
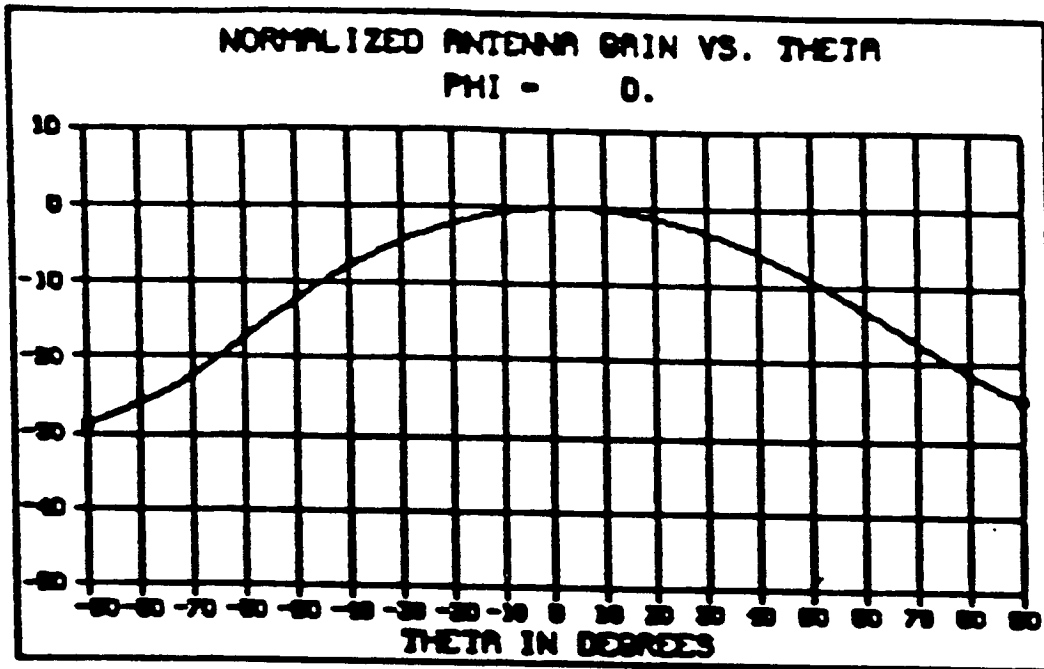
SOFT FAILURES ONLY

2 X 4 ELEMENT S-BAND

FIGURE 3

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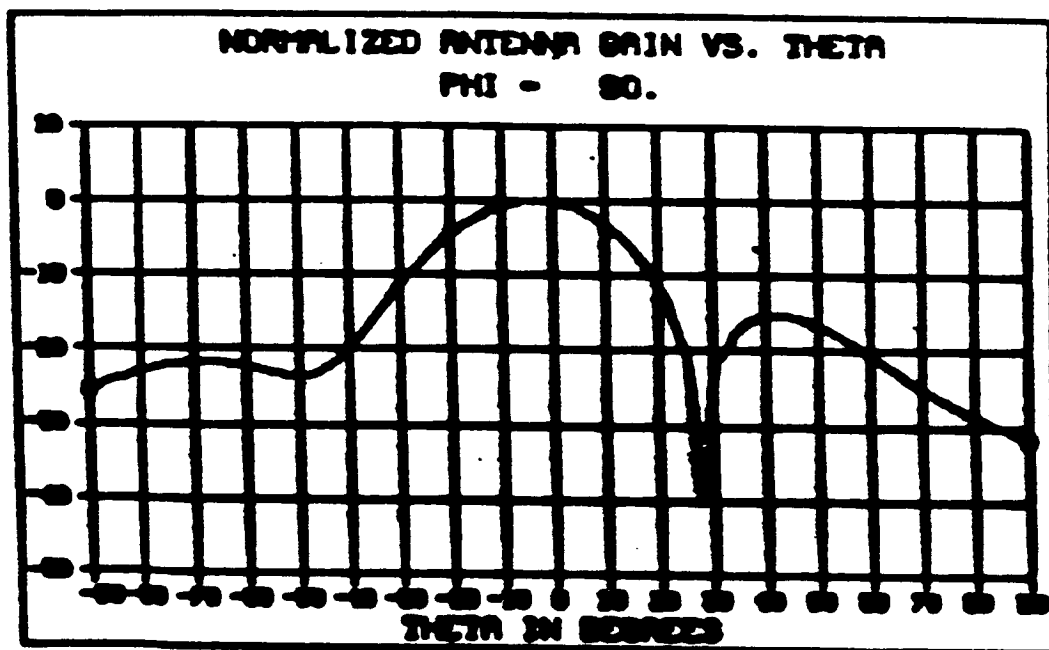
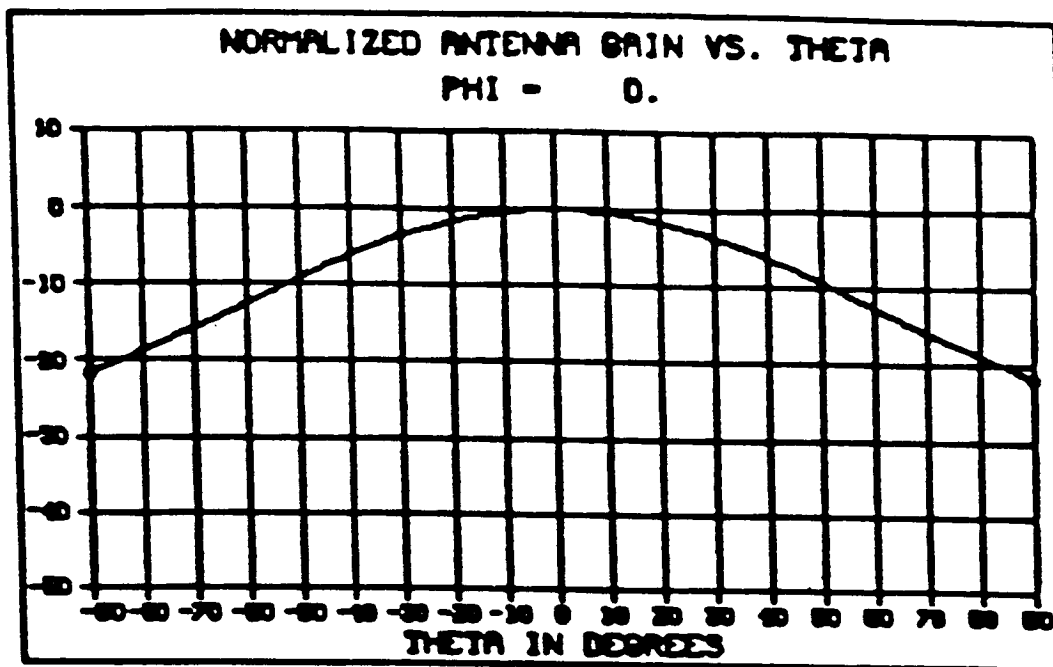
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1 HARD FAILURE, SOFT FAILURES

2 X 4 ELEMENT 8-BAND

FIGURE 4



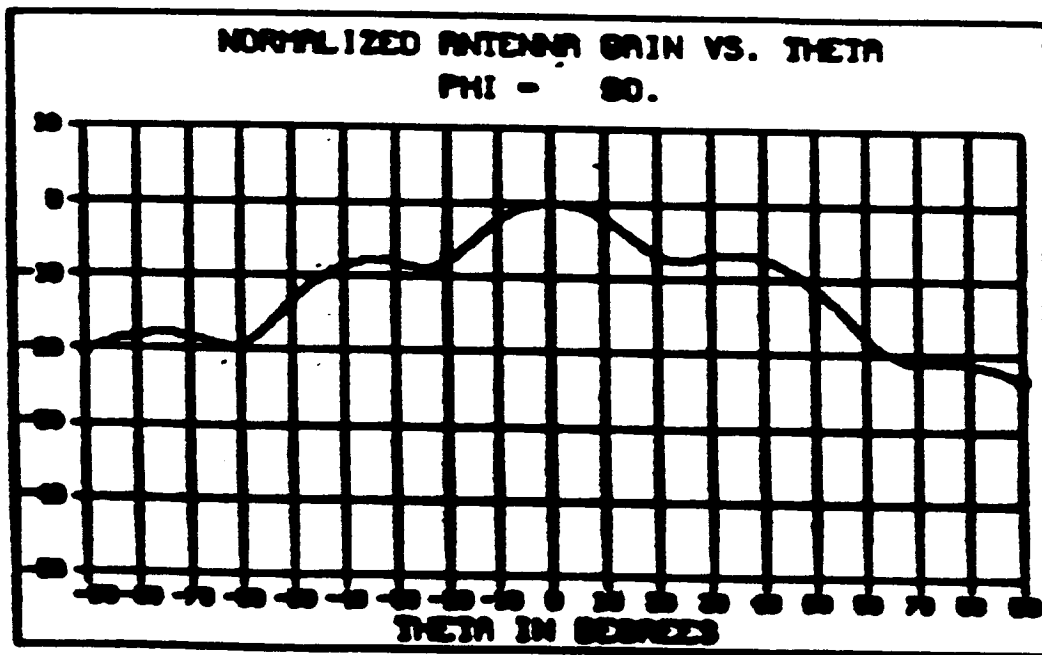
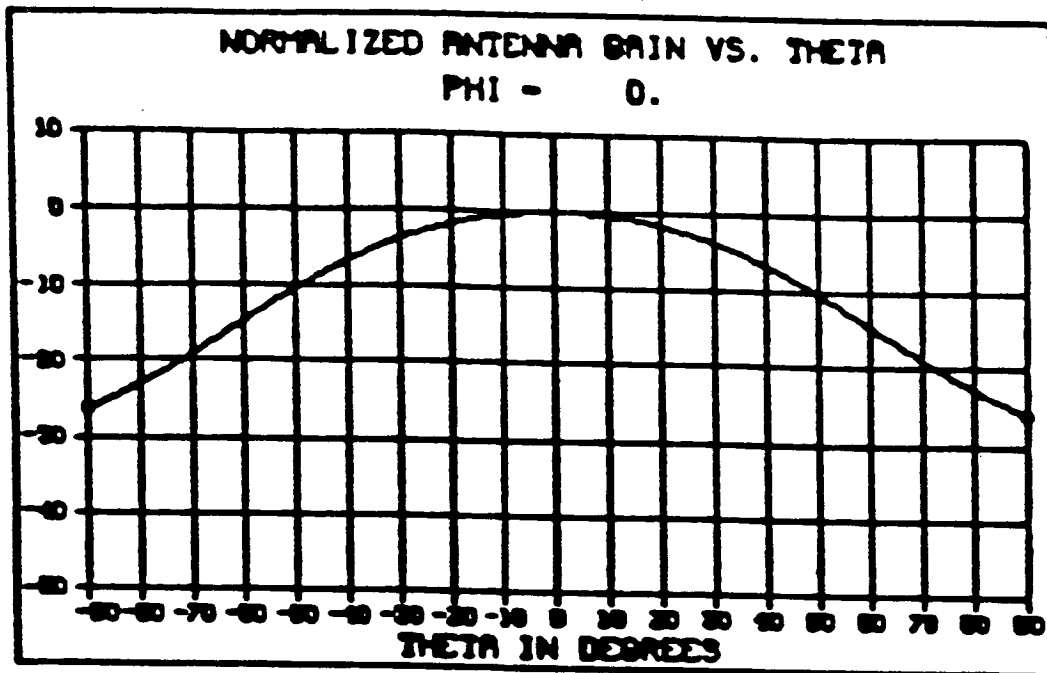
8 HARD FAILURES, 80FT FAILURES

2 X 4 ELEMENT 8-BAND

FIGURE 5

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3 HARD FAILURES, SOFT FAILURES

2 X 4 ELEMENT S-BAND

FIGURE 6